DESIGN AND MODELLING OF A 5MeV RADIO FREQUENCY ELECTRON GUN

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Design and Modelling of a 5MeV Radio Frequency Electron GunIntroduction:

The Accelerator Test Facility (ATF) at Brookhaven National Laboratory is a linac-laser complex for research into laser acceleration and for the generation of coherent radiation from electron beams. In order to achieve the design 50MeV output emittance ($\gamma\sigma_x\sigma_x'$) of less than 3×10^{-5} m. rad. a high brightness electron gun is required. This paper describes computations and measurements made on a full scale brass model of a 1 1/2 cell, π -mode, resonant, disc loaded, radio-frequency gun structure which has been designed for this purpose.

Design Considerations:

In order to achieve high brightness it is necessary to rapidly accelerate electrons from the source, which can be either a conventional thermionic emitter, or a laser driver photo-cathode. Work on d.c. guns^(1,2) has demonstrated that it is extremely difficult to achieve rapid acceleration without serious high voltage breakdown problems. For this reason we propose to design a radio-frequency electron gun similar to that described by Fraser et al⁽³⁾ but operating at a frequency of 2.856GHz instead of 1.3GHz. Tests by J.W. Wang et al on an S-band, standing wave, disc loaded structure at the Stanford Linear Accelerator Center⁽⁴⁾ have shown that high surface gradients, in excess of 300MV/m are attainable for pulsed power systems with pulse lengths of 2.5 μ sec at a pulse repetition rate of 120 p.p.s. Our proposed electron gun design is for a maximum surface field of 120MV/m at a pulse length of 6 μ sec and a pulse repetition rate of 5 p.p.s. This gives us a surface field at the cathode of 101.5MV/m and an energy gain for the 1 1/2 cell Mark I electron gun of 4.93MeV for a peak input power to the gun cavity of 5.45MW. The disc loaded structure was designed to minimize the ratio of the peak surface field to the field at the cathode surface and is not optimized for maximum shunt impedance as is the case for most accelerator structures. Also, we have incorporated a "choke" design in the cathode region so that the metal seal at the cathode mounting flange carries very little current (see Figure 1). To "match" effectively to the π -mode in the 1 1/2 cell structure we have adopted a side wall coupling scheme whereby the standard TE_{10} waveguide mode couples strongly to this mode and where, to a first order, it does not couple to the zero mode. Operation in the π -mode was chosen because beam dynamics computations using PARMELA showed that emittance growth due to radio-frequency defocussing fields in the accelerating gaps was minimized in this mode⁽⁵⁾. The coupling slot extends over the full length of the gun cavity, is 1/2" wide and the inner waveguide surface is tangential to the inner cylindrical surface of the gun cavity. The waveguide is "shorted" approximately one quarter guide wavelength beyond the slot center-line. The cavity design parameters are summarized in Table I.

Design Computations:

The program "SUPERFISH"⁽⁶⁾ has been used to calculate the resonant frequencies, Q values and field distributions for the zero and π -modes in the 1 1/2 cell gun structure without the coupling system. The results of these computations are given in Table II, for the cavity dimensions given in Table III. Since it was expected that the coupling mechanism would significantly modify the resonant frequency and Q value of the π -mode the program

"MAFIA"⁽⁷⁾ was used to model the coupling system. The MAFIA program gave considerably different resonant frequencies for the zero and π -modes of the uncoupled structure as compared to SUPERFISH, though the mode separation was of the same order. These computational results are given in Table IV for a 8.2cm., 1 1/2 cell, test cavity which was built to check out the programs and the coupling systems. Figure 2 shows the field patterns obtained with MAFIA. The measured resonant frequencies are included for comparison with the computational data and agree well with the SUPERFISH data within the mechanical constraints which must be placed on the measured data.

Measurements on the test cavity:

A brass 1 1/2 cell test cavity was constructed in order to test the computations and model the coupling system resonant frequency. Q value and field distribution measurements were made for several different cavity configurations as given in Table V. For each measurement the field was "flattened" or made equal at the cathode surface and the mid-gap of the full cell on axis, in the π -mode. This was achieved by adjusting the penetration of 1/4" diameter tuning screws situated in the side wall of each cell and by a 3/8" diameter screw situated on axis at the end wall, or cathode surface, of the half cell. This screw could, in effect, simulate the final cathode configuration desired. It can be seen from Table V that the frequency of the π -mode was reduced by 7.28MHZ by introduction of the waveguide coupling system and that the zero mode resonant frequency was reduced by a similar amount. In fact this reduction in frequency is entirely due to the coupling slot perturbation as removing the waveguide from the cavity gave essentially the same resonant frequencies as those obtained with the waveguide connected and terminated in a matched load. The final coupling arrangement did not lead to a perfect "match" so a quarter wave matching section was introduced into the waveguide just upstream of the coupling slot in order to improve the match. With this matching section in place, the input VSWR was less than 1.05.

With this final coupling configuration, which is shown in Figure 3, the Q values and resonant frequencies of the zero and π -modes were measured in two ways. First, the power was fed into the gun cavity via the waveguide feed system and the Q value measured by sampling the power coupled into a small loop situated in the side wall of either of the accelerating cells. Second the waveguide was terminated with a matched load and the Q value measured by coupling into one cell and out of the other by small coupling loops placed in the outer wall of each cell. The results are shown in Figure 4.

Note that when we feed through the waveguide the zero mode is essentially suppressed; whereas when feeding through the small loops the zero mode is essentially unaffected by the waveguide system while the π -mode, which couples strongly to the loaded waveguide is reduced in Q value. Also, in order to couple sufficient power into the loaded system to make a good Q measurement it was necessary to use fairly large coupling loops which in themselves reduce the Q value and slightly change the resonant frequencies measured. A separate test of the detuning effect showed that the resonant frequency could be changed by over 1MHz by rotating the loop from minimum to maximum coupling to the cavity modes. In fact we plan to use shorted loop tuners with a tuning range of between 2 and 3 MHz to adjust the cell frequencies and hence the field "flatness" in the Mark I gun cavity which is now under design.

The axial electric field distribution was measured by the perturbation method whereby a small 0.185" diameter bead is moved along the axis and the resonant frequency recorded as a function of bead position. The result for the gun cavity with the final coupling arrangement and with power fed in via the waveguide is shown in Figure 5. Next the effect on the axial electric field caused by detuning one or the other of the individual cells was measured and the results are shown in Figure 6. Then the cavity was placed in an oven and the temperature was increased from 70°F to 105°F in approximately 11°F intervals with the axial field distribution being measured at each temperature. The results which are shown in Figure 7 indicate that there is no change in field distribution with temperature. We plan to operate the Mark I gun at an elevated temperature of approximately 110°F so that the increase in resonant frequency in going from air to vacuum will be exactly cancelled by the reduction in resonant frequency caused by the elevated temperature.

Finally the perturbation technique was used to measure the electric field across the diameter of the gun cavity at four different locations as follows:

- 1) Adjacent to the cathode surface.
- 2) Along the surface opposite the cathode surface in the short cell.
- 3) Along the first surface of the large cell.
- 4) Across the gap center of the large cell.

The results are shown in Figure 8 (a) through (d) and show that there is no asymmetry in the electric field distribution due to the coupling slot; a result which is confirmed by computations made with MAFTA.

Because it is possible to increase the bandwidth of a multicell structure by utilizing a strongly coupled resonant waveguide coupled between adjacent cells of a disc loaded structure, measurements were made on the 1 1/2 cell model to explore this option. For ease of measurement the waveguide was terminated in a fixed short 9.0 cm from the slot centre and the position of an adjustable short on the other end of the waveguide was adjusted over a range of 6 cm in order to vary the resonant frequency of the waveguide cavity, operating in the TE₁₀ mode, over the desired wavelength range. The resonant frequencies of the waveguide mode and the zero and π -modes in the test cavity were measured for each short position and are plotted in Figure 9. The measured resonant frequencies and Q values are also given in Table VI. It can be seen that when the waveguide is exactly resonant at the π -mode resonant frequency of the test cavity the Q value of that mode is, as expected, greatly reduced while the zero mode resonant frequency and Q value is essentially unaffected. It would be possible to increase the bandwidth from 1.85MHz to 2.45 MHz at the expense of a reduction in Q value of about 15% for the π -mode.

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References

1. Charles K. Sinclair and Roger H. Miller, IEEE Transactions on Nuclear Science, Vol.NS-28, No.3, p.2649, June 1981.
2. M.J. Browne et al, IEEE Transactions on Nuclear Science, Vol.NS-32, No.5, p.1829, October 1985.
3. J.S. Fraser et al, IEEE Transactions on Nuclear Science, Vol.NS-32, No. 5, p.1791, October 1985.
4. J.E. Wang and G.A. Loew, IEEE Transactions on Nuclear Science; No.87CH2387-9, p.1854, March 1987.
5. K.T. McDonald - Princeton University Report DOE/ER/3072-43, March 1988.
6. K. Halback, R.F. Holsinger, Particle Accelerators 7 (1976) p.213.
7. T. Barts et al, Proceedings 1986 Linac Conference (SLAC-303) June 1986, p.276.

TABLE OF CONTENTS

- Table I : R.F. Gun Cavity Design Parameters.
- Table II : Model Cavity Experimental and Computational Results.
- Table III: Model cavity dimensions.
- Table IV : Computed and measured resonant frequencies for the 1 1/2 cell model of the gun cavity.
- Table V : Model cavity configurations with measured frequencies and Q value's.
- Table VI : Resonant frequencies and Q value's for a resonant coupling system for different waveguide coupling resonances.
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- Figure 1 : Schematic of the Mark I radio frequency Electron Gun.
- Figure 2 : Field patterns for π -mode resonance as computed by "MAFIA".
- Figure 3 : Final coupling configuration used on the brass model.
- Figure 4 : Resonant frequency plots for final coupling configuration of the test model.
- Figure 5 : Axial electric field distribution in π -mode with the final coupling configuration of the test model.
- Figure 6 : Effects of detuning individual cells.
- Figure 7 : Effect of temperature on axial field distribution.
- Figure 8 : Electric field distribution across the diameter at various locations in the test cavity.
- Figure 9 : Resonant frequencies of the waveguide, zero and π -modes in the gun cavity for various resonant coupled waveguide dimensions.

TABLE I

RF GUN DESIGN PARAMETERS

STRUCTURE TYPE	RESONANT
STRUCTURE INNER DIAMETER, mm	83.08
STRUCTURE LENGTH, mm	78.75
NUMBER OF CELLS	1+1/2
OPERATING FREQUENCY, GHz	2.856
BEAM ENERGY, MeV	4.85
BEAM APERTURE, mm	20
SHUNT IMPEDANCE, MΩ/m	57
CAVITY Q	11,800
MAX. SURFACE ELECTRIC FIELD, MV/m	118
AVERAGE ACCELERATING GRADIENT, MV/m	66.6
ELECTRIC FIELD ON CATHODE, MV/m	100
CAVITY STORED ENERGY, J	3.5
CAVITY PEAK POWER, MW	5.3

MODEL CAVITY EXPERIMENTAL AND COMPUTATIONAL RESULTS - TABLE II

ZERO MODE

CALCULATED RESONANT REFREQUENCY USING SUPERFISH	- 2893.749 MMZ
MEASURED RESONANT FREQUENCY AFTER "FLATTENING" FIELD IN ZERO MODE	- 2896.020 MMZ
Q-VALUE CALCULATED	- 5750
Q-VALUE MEASURED	- 5550

π - MODE

CALCULATED RESONANT FREQUENCY USING SUPERFISH	- 2895.359 MMZ
MEASURED RESONANT FREQUENCY AFTER "FLATTENING" FIELD IN ZERO MODE	- 2897.880 MMZ
Q-VALUE CALCULATED	- 5750
Q-VALUE MEASURED	- 5000

TABLE III MODEL CAVITY DIMENSIONS

CAVITY INNER DIAMETER	82.00 MM
CAVITY LENGTH	78.75 MM
CAVITY APERTURE	20.00 MM
DISC THICKNESS	20.00 MM
DISC RADIUS	9.53 MM
WAVEGUIDE BROAD DIMENSION	72.18 MM
WAVEGUIDE NARROW DIMENSION	34.08 MM
COUPLING SLOT WIDTH	12.70 MM
COUPLING SLOT LENGTH	68.75 MM

<u>CONFIGURATION</u>	<u>RESONANT FREQUENCIES (MHZ)</u>	
	<u>ZERO MODE</u>	<u>π-MODE</u>
1 1/2 CELL STRUCTURE WITHOUT WAVEGUIDE COUPLING SYSTEM	2893.04	2894.95 (SUPERFISH)
	2896.02	2877.00 (MAFIA)
1 1/2 CELL STRUCTURE WITH WAVEGUIDE COUPLING SYSTEM		2897.88 (MEASURED)
	2888.43	2871.02 (MAFIA)
		2890.30 (MEASURED)

TABLE IV - COMPUTED AND MEASURED RESONANT FREQUENCIES FOR THE 1 1/2 CELL MODEL OF THE GUN CAVITY.

SUMMARY OF RESONANT FREQUENCY AND Q-VALUE DATA FOR THE ELECTRON GUN TEST CAVITY

CAVITY CONFIGURATION	RESONANT FREQUENCY (MMZ)		MEASURED Q-VALUE	
	ZERO-MODE	π - MODE	ZERO-MODE	π - MODE
NO WAVEGUIDE, COUPLING VIA SMALL LOOPS; FIELD "FLAT" IN ZERO MODE	2896.02	2897.88	5525	5175
WAVEGUIDE CONNECTED AND TERMINATED AND COUPLED THROUGH 1/2" DIA. HOLES IN BOTH CELLS, MEASURED VIA SMALL LOOPS; FIELD "FLAT" IN π - MODE (SHORT AT 24cm.)	2892.92	2894.72	5350	4670
FINAL CONFIGURATION: WAVEGUIDE CONNECTED AND TERMINATED AND COUPLED THROUGH 1/2" WIDE SLOT COVERING BOTH CELLS. ALSO A 1/4" RADIUS HEMISPHERICAL HOLE CONNECTS THE TWO CELLS AT THE COUPLING SLOT. MEASURED VIA SMALL LOOPS; FIELD "FLAT" IN π - MODE AND WAVEGUIDE SHORT AT 24cm.	2888.45	2890.29	2490	2190
AS ABOVE BUT WITH WAVEGUIDE SHORT REDUCED TO 9.0cm FROM SLOT CENTER	2888.43	2890.30	2600	2400
REPEAT MEASUREMENT AFTER REASSEMBLING AND RETUNING CAVITY	2887.72	2889.50	3700	2750

SHORT POSITION (cm)	APPROXIMATE LENGTH OF SHORT ($2\lambda_g$) (cm)	f, CALCULATED FROM SHORT (MHZ)	WAVE GUIDE RES. FREQ. (MHZ)	ZERO MODE RES. FREQ. (MHZ)	PI-MODE RES. FREQ. (MHZ)
0	28.5	2972.1	2964.7	2890.22	2891.95
0.5	29.0	2946.5	2944.7	2890.22	2891.89
1.0	29.5	2922.0	2919.0	2890.23	2891.77
1.25	29.75	2910.1	2905.8	2890.20	2891.49
1.4	29.90	2903.1	2890.3	2890.00	2893.18
1.5	30.00	2898.5	2890.6	2890.18	2895.10
1.75	30.25	2887.1	2880.9	2890.17	2892.63
2.0	30.5	2876.0	2869.8	2890.18	2892.34
2.5	31.0	2854.3	2847.4	2890.18	2892.18
3.0	31.5	2833.6	2824.7	2890.18	2892.10
3.5	32.0	2813.7	2801.9	2890.18	2892.07
4.0	32.5	2794.5	2781.5	2890.18	2892.07
4.5	33.0	2776.1	2761.7	2890.18	2892.04
5.0	33.5	2758.4	2742.5	2890.18	2892.01

TABLE VI MEASURED TEST CAVITY AND WAVEGUIDE RESONANT FREQUENCIES AS A FUNCTION OF SHORT POSITION OR WAVEGUIDE RESONANT FREQUENCY.

FINAL Q PLOTS WITH WAVEGUIDE FEED

AXIAL FIELD WITH SHORT AT 3.25cm

AXIAL E FIELD VS CELL DETUNING

AXIAL E FIELD VS CAVITY TEMPERATURE

E FIELD ALONG CATHODE SURFACE

E FIELD ALONG SURFACE OPPOSITE CATHODE

E FIELD ALONG FIRST WALL OF LARGE CELL

E FIELD ACROSS GAP CENTRE OF LARGE CELL

RESONANT FREQUENCIES MEASURED WITH

RESONANT WAVEGUIDE COUPLER